Collaborative Research: Assessing Oceanic Predictability Sources for MJO Propagation
Final Report

1. General information

Project title:	Collaborative Research: Assessing Oceanic Predictability Sources for Madden–Julian Oscillation Propagation
PI/co-PI names and institutions:	Charlotte DeMott (Colorado State University) and Nicholas Klingaman (University of Reading)
Report Year:	FY19, Year 4 Progress Report (no-cost extension)
Grant #:	NA16OAR4310094

2. Accomplishments

2.1. Main goals of the project, as outlined in the funded proposal

Goal 1: Evaluate S2S database ensemble prediction skill for three types of Madden–Julian Oscillation (MJO) events—strong propagating, weak propagating, and eastward-decaying—with regards to atmospheric and oceanic precursor signals.

Goal 2: Test the roles of specific oceanic feedback processes for MJO prediction skill using coupled models with a demonstrated ability to simulate the MJO.

Goal 3: Adapt a set of MJO air–sea interaction diagnostics developed by the PIs for analysis of climate simulations to hindcast simulations.

2.2. Results and accomplishments

2.2.1 Fundamental advances in understanding how ocean feedbacks affect the MJO

Work performed as part of this project has resulted in significant new understanding of how ocean feedbacks affect the MJO. As detailed in *DeMott et al.* (2019), **high-frequency (i.e., submonthly) ocean coupling yields tropical mean state moisture patterns that are more peaked on the Equator than in uncoupled simulations** (Figure 1). The resulting sharper meridional moisture gradients promote MJO propagation through column moistening by meridional advection of mean state moisture by meridional wind anomalies. By identifying the principal role of high-frequency ocean feedbacks in setting the mean state moisture distribution, this finding reconciles previously conflicting paradigms of the MJO as either a predominantly atmospheric moisture mode or as an intrinsically ocean-atmosphere coupled phenomenon.

Additional work led by Co-PI Klingaman using the super-parameterized Community Climate Model (SPCCSM, version 3) and published published in a second paper supported by this project (*Klingaman and DeMott*, 2020) demonstrated that **ENSO-driven low-frequency SST perturbations are paramount to a model's perceived ability to simulate the MJO**. In particular, robust MJO propagation only occurred when the SPCCSM atmosphere model coupled to many columns of 1D K-profile parameter (KPP) mixing

model was constrained to a repeating three-year ENSO cycle, or to a perpetual El Niño state, emphasizing the strong influence of El Niño on MJO propagation. MJO propagation in simulations constrained to the coupled model El Niño state remained robust regardless of whether or not high-frequency ocean coupled feedbacks were included, indicating that feedbacks from low-frequency ocean variability are more important to the MJO than those from high-frequency variability.

The findings of *Klingaman and DeMott* (2020) are consistent with the results of a third paper supported by this project (*DeMott et al.*, 2018) that demonstrated that changes to observed tropical mean state moisture patterns during El Niño and La Niña conditions are respectively associated with either enhanced or muted MJO propagation beyond the Maritime Continent. The key factor for setting the El Niño vs La Niña MJO propagation differences is the change to the meridional distribution of moisture across the Warm Pool with ENSO phase. A related paper supported by this project, in collaboration with a postgraduate student in China, confirmed that many of these same sensitivities to air–sea coupling and ocean basic state also hold for the dominant mode of boreal summer intraseasonal variability, the Boreal Summer Intraseasonal Oscillation (BSISO; *Gao et al.*, 2020).

Together, these studies offer a new perspective for assessing ocean sources of predictability for the MJO. Given the well-documented role of mean state meridional moisture gradients for MJO propagation and the high correlation of mean state column water vapor and mean state SST across the tropics, diagnosing SST drift in forecast models may provide insights into processes responsible for the degradation of MJO forecast skill with lead time.

2.2.2 New assessments of ocean feedbacks to MJO prediction skill

Climatological SST drift in S2S forecast models was analyzed to understand how climatological drift in the net surface energy budget, Q_{net}, and ocean dynamics each contribute to the SST drift. Climatological SST tendencies as a function of lead time (i.e., the drift) were regressed onto Q_{net} as a function of lead time to estimate the component of SST drift driven by Q_{net}. SST drift not linearly related to Q_{net} (i.e., the residual) is assumed to be driven by ocean dynamics. Q_{net} drift can be further decomposed into its radiative and surface flux components. This diagnostic is illustrated in Fig. 2 for a region of the western Indian Ocean for two S2S member models. This diagnostic has been applied to all latitude-longitude grid points for several coupled S2S models, and the results indicate substantial model-to-model differences in the sign, magnitude, spatial pattern, and Q_{net} vs ocean dynamics contributions to SST drift. The spread in Q_{net} regulation of SST drift in particular highlights the large influence of model cloud processes on SST drift in coupled forecast models.

Co-PI DeMott is informally collaborating with Magdalena Balmaseda and Frederic Vitart of ECMWF to apply this diagnostic to output from a series of observing system sensitivity experiments with the ECMWF forecast model.

Other evaluations of ocean sources of predictability on MJO forecast skill have also been performed. These included evaluations of MJO forecast skill as a function of ENSO state, SST anomaly forecast skill, the fidelity of the SST initial state, and the presence of eastward or westward equatorial surface currents in the Indian Ocean and their influence on SST warming or cooling, respectively, by zonal temperature advection. As documented in annual progress reports for this project, we found no oceanic source of predictability common to all models in these evaluations whether skill was assessed for all or individual MJO RMM phases. Rather, the prevailing finding is that ***intermodel differences in MJO forecast skill for a given ocean state far exceed skill differences in contrasting ocean states***, e.g., El Niño vs La Niña, or eastward vs westward surface currents, even when observed MJO events have been shown to evolve
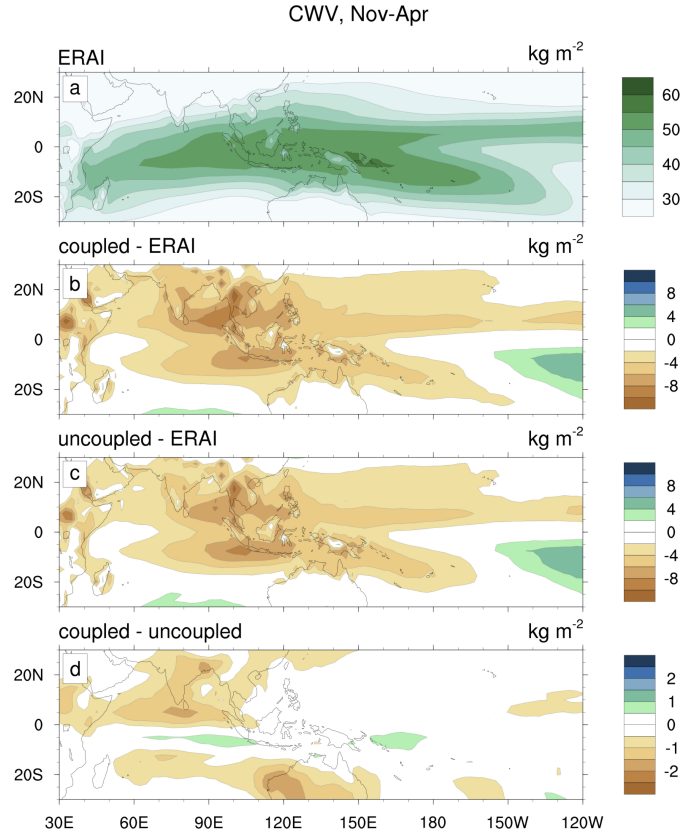
Figure 1: November–April averaged column water vapor (CWV) for a) ERA-Interim reanalysis, multi-model mean CWV bias for b) coupled and c) uncoupled simulations, and d) coupled minus uncoupled CWV difference for the four model simulations pairs described in *DeMott et al.* (2019). For each model, monthly mean SSTs from the 20–25 years of the coupled simulation are prescribed to the uncoupled simulation to ensure that coupled and uncoupled simulations have identical SST mean state and low-frequency variability.
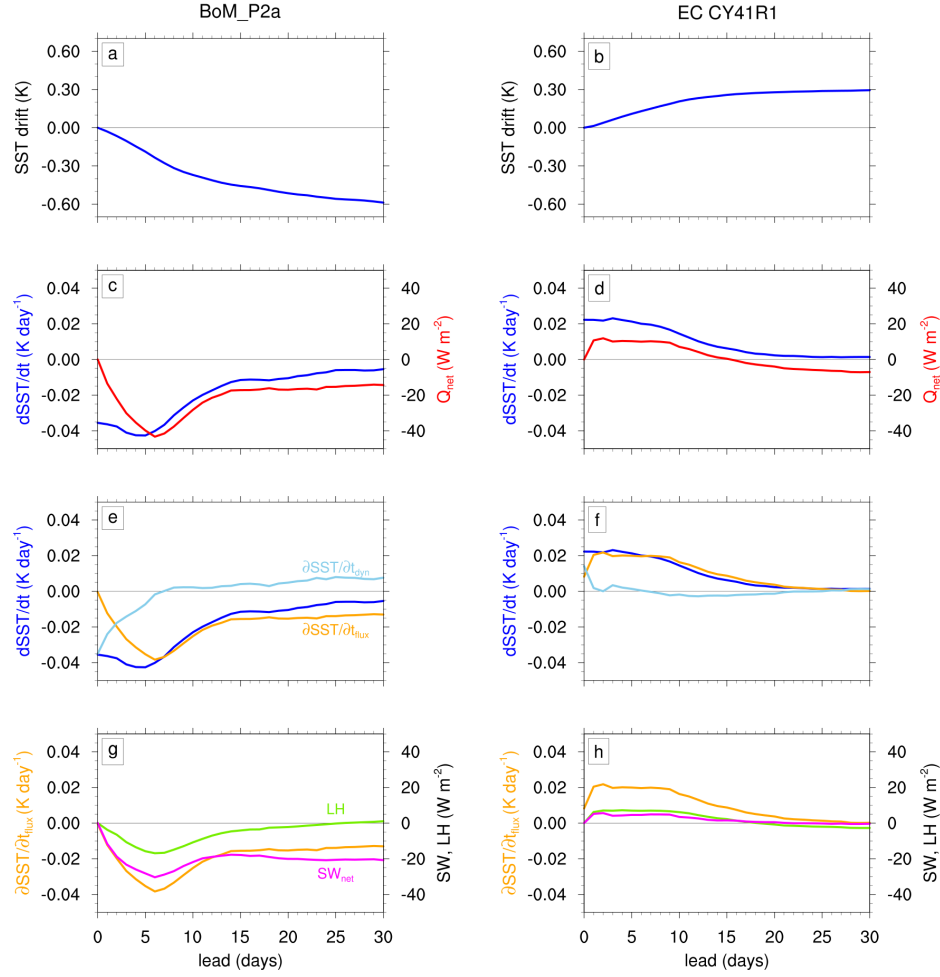
Figure 2: a–b) November–April mean SST drift, c–d) SST tendency (blue) and Q_{net} (red), e–f) SST tendency (red; repeated from c and d, respectively), and their contributions from Q_{net} (orange) and ocean dynamics (light blue), g–h) Q_{net} (orange; repeated from e and f, respectively), surface net shortwave heating (magenta) and latent heat flux (green) as a function of lead time averaged over the western Indian Ocean box shown in Figure **??**.

differently in these contrasting ocean states. These findings indicate to us that biases in model physics, intialization strategies, or both currently obscure ocean feedbacks that may provide sources of skill for MJO forecasts in future, refined coupled forecast models. Focused effort to reveal sources of these biases, such as those revealed with our framework for assessing SST drift, may be required to improve MJO forecast skill with coupled models.

2.2.3 New framework for testing specific ocean feedbacks to the MJO in a coupled forecast model

We developed a method of testing specific SST feedback processes in coupled forecast models by masking various aspects of SST variability (intraseasonal variability, dirunal cycle, spatial gradients) from the surface latent and sensible heat flux calculations and evaluating their effects on MJO prediction. This framework was tested using the MetUM coupled to a 1-dimensional K-profile parameterization (KPP) ocean mixing model at each atmospheric grid column and applied to MJO events observed during the DYNAMO field campaign (1 October - 5 December 2011 and 1 February - 20 March 2012).

We ran the following experiments:

- CPL-CTL: Standard coupled control with KPP ocean

- ATM-DAY: Atmosphere-only with persisted initial SST from the daily value on the first day of the forecast

- ATM-BGD: Atmosphere-only with persisted initial SST from the background value (71-day running mean) on the first day of the forecast.

- CPL-NoDC: Coupled experiment with daily mean SST only (no diurnal cycle of atmosphere–ocean interactions)

- CPL-NoZG: Coupled experiment with the zonal gradient of intraseasonal SST removed in the Indo-Pacific Warm Pool

- CPL-NoMG: Coupled experiment with the meridional gradient of intraseasonal SST removed in the Indo-Pacific Warm Pool

Compared to the fully coupled simulation (CPL-CTL), the effects of SST temporal smoothing became progressively more detrimental to MJO forecast skill with the removal of diurnal, then intraseasonal, and all SST variability. For the CPL-NoDC experiment, MJO skill degradation, although generally small, was larger when the SST diurnal cycle was masked from the surface sensible heat fluxes than for surface latent heat fluxes. This is consistent with the idea that peak diurnal SST anomalies during MJO suppressed conditions destabilize the lower atmosphere and initiate convection and low-level moistening through detrainment and compensating low-level convergence.

Removing the meridional gradient of intraseasonal SST (CPL-NOMG) had a very limited effect on forecast performance (Figure 3c). Removing the zonal gradient of intraseasonal SST (CPL-NOZG) produced much more substantial degradations in performance (Figure 3d), equivalent to the entire two days of lead time difference between CPL-CTL and ATM-DAY in Figure 3a). Removing the zonal gradient of SST for only the LHF computation (CPL-NOZG-LHF) produced an even larger degradation than removing the gradient for both SHF and LHF, suggesting that the effect of the zonal intraseasonal SST gradient is communicated primarily through changes in atmospheric convection and moisture gradients.
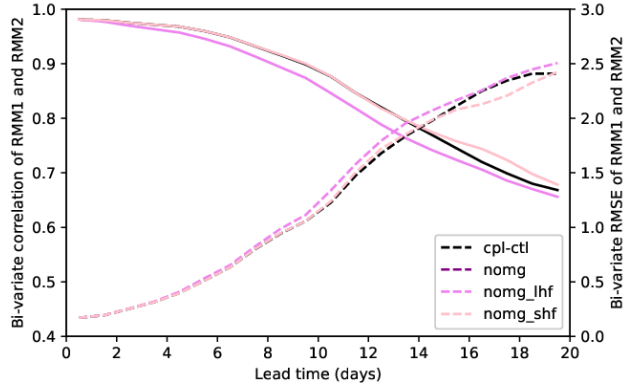
a. Coupled vs. atmos-only
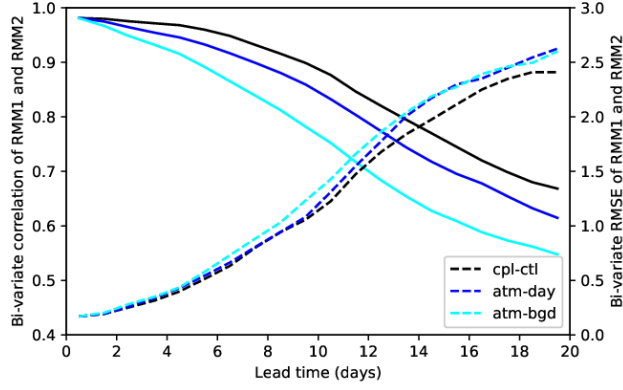
b. Effect of diurnal cycle
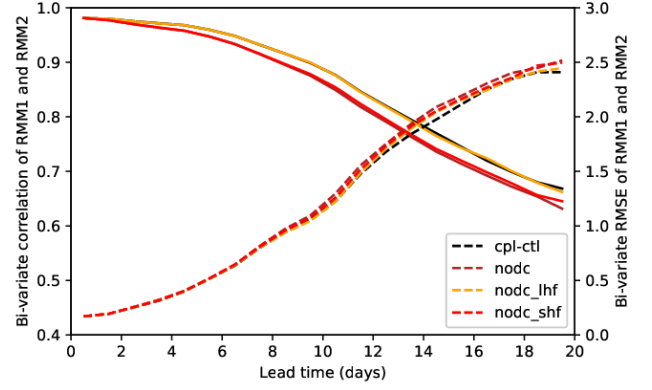
c. Effect of meridional SST gradient
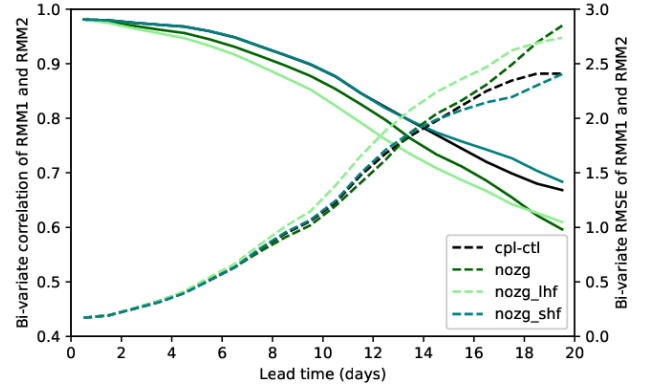
d. Effect of zonal SST gradient

Figure 3: Bi-variate RMM correlations (left axis, solid lines) and RMSEs (right axis, dashed lines) for MetUM experiments against observations. Panels show comparisons of CPL-CTL (black lines) against (a) ATM-DAY (blue) and ATM-BGD (cyan); (b) CPL-NODC (dark red), CPL-NODC-SHF (red) and CPL-NODC-LHF (light orange); (c) CPL-NOMG (dark purple), CPL-NOMG-LHF (purple) and CPL-NOMG-SHF (pink); (d) CPL-NOZG (dark green), CPL-NOZG-LHF (green) and CPL-NOZG-SHF (teal).

3. Products

3.1. Publications, conference papers, and presentations

Publications (including in-progress)

DeMott, C. A., B. O. Wolding, E. D. Maloney, and D. A. Randall, 2018: Atmospheric mechanisms for MJO decay over the Maritime Continent. *J. Geophys. Res. Atmos*, **123**. https://doi.org/10.1029/2017JD026979.

DeMott, C. A., N. P. Klingaman, W.-L. Tseng, M. Burt, and D. A. Randall, 2019: The convection connection: How ocean feedbacks affect tropical mean moisture and MJO propagation. *J. Geophys. Res. Atmos*, **124**. https://doi.org/10.1029/2019JD031015

Subramanian, A. C., and co-authors, 2019: Ocean Observations to Improve Our Understanding, Modeling, and Forecasting of Subseasonal-to-Seasonal Variability. *Front. Mar. Sci.*, 08 August 2019. https://doi.org/10.3389/fmars.2019.00427.

Klingaman, N. P., and C. A. DeMott, 2020: Mean-state biases and interannual variability affect perceived sensitivities of the Madden–Julian oscillation to air–sea coupling. Journal of Advances in Modeling Earth Systems, 12, e2019MS001799. https://doi.org/10.1029/2019MS001799

Gao, Y., Klingaman, N. P., DeMott, C. A. and Hsu, P.-C., 2020: Boreal summer intraseasonal oscillation in a superparameterized general circulation model: effects of air–sea coupling and ocean mean state. Geoscientific Model Development, 13, 5191–5209. https://gmd.copernicus.org/articles/13/5191/2020/

DeMott, C. A., and N. P. Klingaman, 2020: SST drift in coupled forecast models and its affect on subseasonal MJO prediction skill. In preparation.

Conference Presentations

DeMott, C. A., and N. P. Klingaman, 2017: Oceanic sources of predictability for MJO propagation across the Maritime Continent in a subset of S2S forecast models. American Geophysical Union Annual Meeting, 11–15 December 2017, New Orleans, LA, USA.

DeMott, C. A., and N. P. Klingaman, 2018: The ocean-atmosphere dialog in the MJO: Physical processes vs systematic biases in forecast models. WCRP International Conference for Subseasonal to Decadal Prediction, Boulder, CO, USA, 17-21 September 2018.

Klingaman, N. P. and C. A. DeMott, 2019: Why do air–sea interactions improve predictions of the MJO? US CLIVAR Tropical Convection and Air–Sea Interaction Workshop, Boulder, CO, USA, 7–9 May 2019.

DeMott, C. A., N. P. Klingaman, and H. H. Hendon, 2019: Assessing SST forecast skill in the Warm Pool with the S2S database. Asia-Oceania Geophysical Society Annual Meeting, Singapore, 29 July–2 August 2019.

Klingaman, N. P. and C. A. DeMott, 2019: Why do air–sea interactions improve predictions of the MJO? Asia-Oceania Geophysical Society Annual Meeting, Singapore, 29 July–2 August 2019.

DeMott, C. A. and N. P. Klingaman, 2020: Warm Pool SST Forecast Skill in S2S Models: Mean State Drift versus Anomaly Patterns. American Meteorological Society Annual Meeting, 13–16 January, 2020, Boston, MA, USA.

DeMott, C. A., 2020: Ocean influence on MJO prediction. S2S Prediction Project webinar series, 24 June 2020 (virtual presentation).

3.2. Technologies or Techniques

- SST drift diagnosis (Section 2.2.2)

- Ocean feedback sensitivity testing framework (Section 2.2.3)

3.3. Inventions, patents, licenses

Nothing to report.

3.4. Other products

Nothing to report.

4. Participants and other collaborating organizations

Individuals funded by this project:

- Charlotte DeMott, CSU

- Nicholas Klingaman, UofR

- William Keat, UofR

- Jonathan Shonk, UofR

There were no changes in the active other support of PIs or other senior/key personnel during the project.

No other organizations were involved as partners.

We collaborated informally with Magdalena Balmaseda and Frederic Vitart of ECWMF, as well as with Yingxia Gao and Pang-Chi Hsu of Nanjing University of Information Science and Technology (NUIST, China).

5. Impact

The primary impact of this work is the new understanding of how coupled ocean feedbacks affect mean state moisture patterns and MJO propagation. This finding suggests that improved understanding of how convection responds to submonthly SST-driven buoyancy fluctuations in the atmospheric boundary layer, and improving the representation of those responses in climate and forecast models will be the most fruitful way forward for improving MJO predictions.

Our findings will also impact the ocean modeling community by providing evidence of ocean model biases that affect the ocean-to-atmosphere buoyancy flux.

Our project supported the training and development of one post doctoral researcher at the University of Reading.

There were no impacts on teaching or education resources, infrastructure, or technology transfer.

The impact on society beyond science and technology transfer include guidance for improving subseasonal forecasts for the benefit of commercial activity and public health and safety.

100% of the CSU budget was spent in the US. 100% of the UofR budget was spent in the UK.

6. Changes or Problems

Our initial efforts to establish a baseline assessment of ocean feedbacks to the MJO in observations led to important breakthroughs in understanding the role of the ocean for the MJO. This ended up being prolonged work that provided fundamental insights into a decades-old question regarding the MJO. These findings will provide a useful paradigm for understanding MJO prediction skil in future studies, even though the effort required to advance the science took time away from detailed analysis of the S2S database. Our analysis of the S2S database ultimately revealed that many of the proposed ocean feedback mechanisms described in our original proposal are not evident in the S2S database (Section 2.2.2). We empahsize that this finding does not disprove the theoretical bases for these feedbacks. Rather, it suggests that the degradation of MJO forecast skill with lead time is currently so heavily influenced by biases in model physics—most likely those associated with parameterized convection—and initialization shock adjustments that the effects of ocean feedbacks cannot be discerned.

There were no changes that caused significant impact on expenditures or location of the work. This study involved no human subjects.

7. Project Outcomes

Our project significantly advanced understanding of how ocean coupled feedbacks interact with the tropical Madden-Julian oscillation (MJO). Variations in sea surface temperature (SST) on timescales shorter than one month regulate the frequency and intensity of atmospheric convection, and the depth at which evaporation of cloud droplets and rainfall moisten the tropical environment. In experiments with four different models, this SST regulation of convection in coupled simulations led to enhanced moistening near with the Equator compared to less moistening, or drying off of the Equator. These changes to mean state moisture patterns lead to enhanced moisture advection by anomalous poleward flow east of MJO convection and improved eastward propataion of the MJO compared to uncoupled simulations.

Our project also identified what appears to be an important, and likely overlooked, connection between SST patterns associated with simulated El Niño–Southern Oscillation (ENSO) variability and the perceived skill with which that model simulates the MJO. Using a model that simulates a highly realistic MJO (the superparameterized Community Climate System Model, SPCCSM version 3), we demonstrated that MJO skill in that model is almost entirely due to robust MJO propagation that occurs during El Niño conditions. This low-frequency SST regulation of the MJO is likely the result of the steeper eastward moisture gradient and the eastward expansion of the Warm Pool during El Niño conditions; the former supports extended eastward propagation of MJO convection through enhanced zonal moisture advection, while the latter maintains MJO convection against dissipation over a greater distance than during normal or La Niña conditions.

We analyzed ocean feedbacks to the MJO using eleven to 20 years worth of historical reforecasts from five coupled forecasts models that contributed to the international subseasonal-to-seasonal (S2S) database.

Many presumed ocean sources of predictability to the MJO were not widely evident among the models we analyzed. Expected differences in MJO evolution in forecast models for contrasting ocean conditions, such as El Niño vs La Niña, or eastward or westward surface currents in the Indian Ocean, were also highly model-dependent. With these findings, we surmise that deficiencies in model physics or initialization methods have a larger impact on MJO prediction skill than sources of skill that may arise from ocean feedbacks.

Finally, we developed a framework to test MJO prediction skill dependence on SST variability for a variety of temporal scales and spatial patterns, including whether the SST feedbacks are more strongly felt through their effect on surface latent or sensible heat fluxes. Future experiments using this approach should examine how the results affect spatial patterns of mean state moisture.

8. Budget Summary

8.1. University of Reading Budget

Item	Yr1 (Jul16–Jun17) Spend (notes)	Yr2 (Jul17–Jun18) Spend (notes)	Yr3 (Jul18–Jun19) Spend (notes)	Yr4 (Jul19–Jun20) Spend (notes)
Klingaman salary and fringe	$0 (Provided at no cost)	$0 (Provided at no cost)	$0 (Provided at no cost)	$0 (Provided at no cost)
Post-docs (Keat and Shonk) salary and fringe	$0	$0	$29,136 (7.2 months)	$0
Travel	$0	$0	$3167 (CLIVAR Air-sea interaction workshop (Boulder CO; May 2019))	$0
Other Direct Costs	$0	$0	$0	$22
Indirect Costs	$0	$0	$40,342	$13,447
Total projected spending	$0	$0	$72,645	$13,470

Total projected spending through end of Year 4: $86,115
Total unspent funds at End of Year 4: $17,256

References

DeMott, C. A., B. O. Wolding, E. D. Maloney, and D. A. Randall (2018), Atmospheric mechanisms for MJO decay over the Maritime Continent, *Journal of Geophysical Research*, *123*, 5188–5204, doi: 10.1029/2017JD026979.

DeMott, C. A., N. P. Klingaman, W.-L. Tseng, M. Burt, and D. A. Randall (2019), The convection connection: how ocean feedbacks affect tropical mean moisture and MJO propagation, *Journal of Geophysical Research*, *124*, 11,910–11,931, doi:10.1029/2019JD031015.

Gao, Y., N. P. Klingaman, C. A. DeMott, and P.-C. Hsu (2020), Boreal summer intraseasonal oscillation in a superparameterized general circulation model: effects of air–sea coupling and ocean mean state, *Geoscientific Model Development*, *13*, 5191–5209, doi:10.5194/gmd-13-5191-2020.

Klingaman, N. P., and C. A. DeMott (2020), Mean-state biases and interannual variability affect perceived sensitivities of the Madden–Julian oscillation to air–sea coupling, *Journal of Advances in Modelling Earth Systems*, *12*, e2019MS001,799, doi:10.1029/2019MS001799.